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14. ABSTRACT

An innovative approach to 3-legged mobility was developed which enables a variety of novel and useful gaits and mobile manipulation strategies.
A variable length cam concept was realized in a prototype version showing how it could be realized with commercially available off the shelf components. The mechanism can be further improved through the use of custom designed components, which would decrease overall system weight and increase performance.

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Bill Ross
UU	UU	UU	UU		19b. TELEPHONE NUMBER 518-891-5889

Report Title

Triple Compliant Limbs with Adaptive Body Structure Final Report

ABSTRACT

An innovative approach to 3-legged mobility was developed which enables a variety of novel and useful gaits and mobile manipulation strategies.
A variable length cam concept was realized in a prototype version showing how it could be realized with commercially available off the shelf components. The mechanism can be further improved through the use of custom designed components, which would decrease overall system weight and increase performance.
Further inertial energy losses can be mitigated by reducing gear and drivetrain weights. A gear testing device was developed which will provide loading data for gears made of various materials under normal and cyclic loads. The results from this test can lead the design of efficient gear trains with minimal moments of inertia.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Two presentations at DARPA-sponsored M3 meetings.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Michael D. Taylor	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
William Ross	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
David Rice	0.20
Gabriel Goldman	0.05
FTE Equivalent:	**0.25**
Total Number:	**2**

Sub Contractors (DD882)

Inventions (DD882)

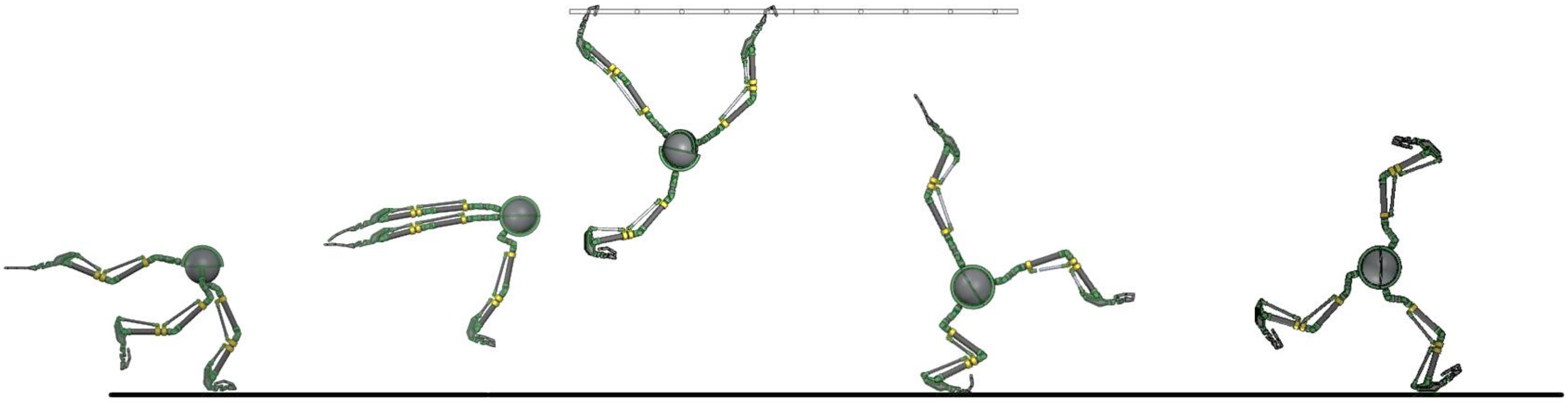
Scientific Progress

Technology Transfer

Triple Compliant Limbs with Adaptive Body Structure

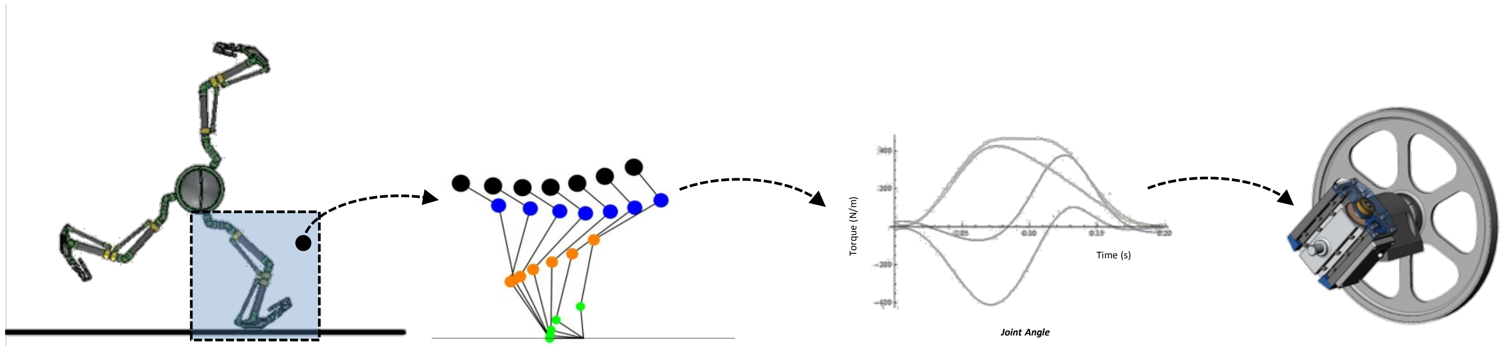
PI: B. Ross Co-PI: H. Geyer

Gabriel Goldman, David Rice



Overview

In this report, a novel <u>triple-limbed robot with compliant joint structure </u>is shown which is capable of a variety of locomotion gaits while retaining the capability to perform manipulation tasks.



Novel Gait Concept ***Gait Development*** ***Gait Analysis*** ***Mechanism Development***

A <u>novel running gait </u>is demonstrated which illustrates the high-speed capability of a triple-limbed robot.

The resulting gait is <u>analyzed</u> to determine the mechanical requirements for the system

A <u>novel mechanism</u> is developed which is capable of producing the triple-limbed gait while maintaining a high level of efficiency

Test results of a prototype of the mechanism is shown to validate the concept as well as demonstrate the fine manipulation capabilities of the system

DARPA

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Motivation

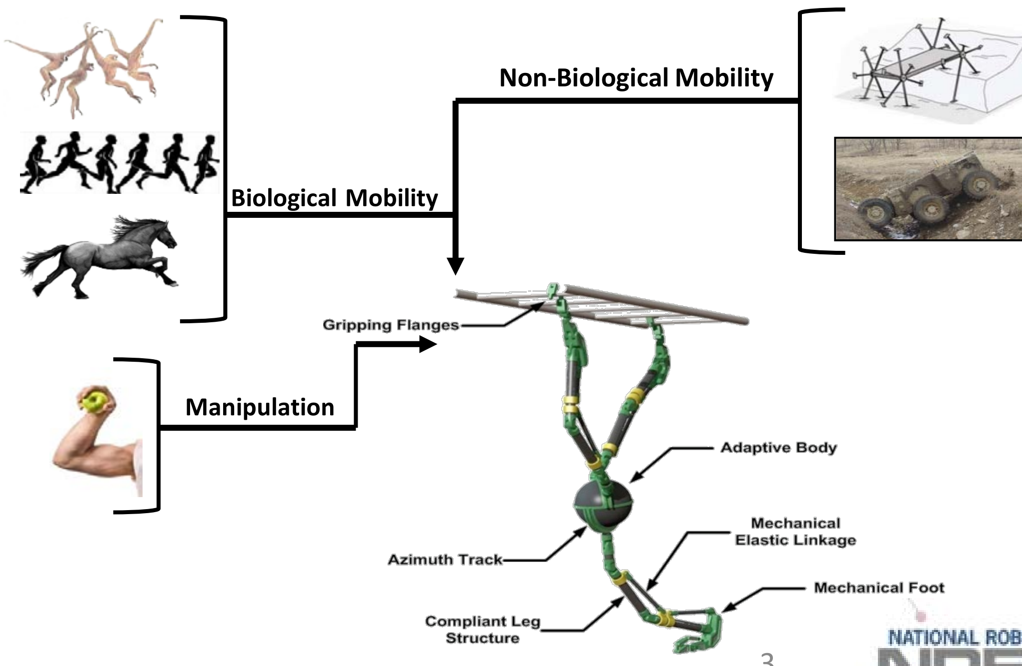
Novel Triple-Compliant Limbed Robot

Maximum mobility is often evaluated in comparison to animal performance. However, while animals have evolved into impressive performers, evolution should not limit the potential for maximum mobility.

For instance, animals have never developed legs that can freely rotate around their own axis; nor have they evolved odd numbers of legs, or limbs that branch out into multiple and specialized feet or hands.

This evolutionary constraint has limited the scientific and technological paradigm of legged dexterity as we know it today, creating an unexplored potential for maximum mobility.

We seek to overcome biological limitations and explore maximum mobility by combining compliant, multi-segment limbs and their control with a tri-limb body that can adapt its limb configuration in unusual and surprising ways to suit maximum mobility tasks.



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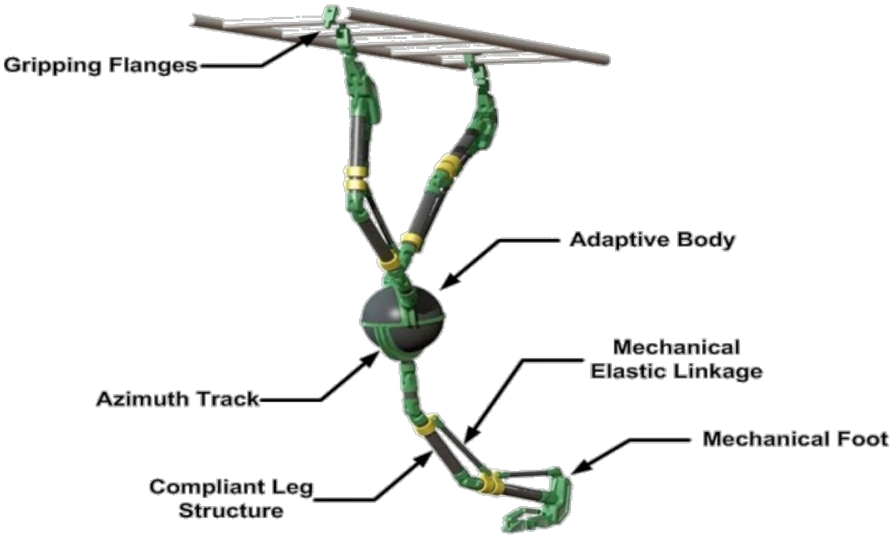
System Concept

Novel Triple-Compliant Limbed Robot

The triple-limb compliant robot concept has three identical limbs that are capable of either locomotion or manipulation tasks (or a combination of both)

- **Adaptive Body:** Capable of orienting the limbs into positions that can be used for manipulation or locomotion tasks.
- **Azimuth Track:** Allows for positioning of limb around the perimeter of the adaptive body structure.
- **Compliant Limb Structure:** Limb is comprised of several links driven by mechanical elastic linkages which are able to store and release energy during mobility tasks.
- **Mechanical Elastic Linkage:** Stores and releases mechanical energy from impacts.
- **Mechanical Foot:** Provides compliant surface for contact with the ground during mobility tasks
- **Gripping Flanges:** Front segments of the mechanical foot can be used to grip objects for manipulation tasks or grip the environment for novel mobility tasks.

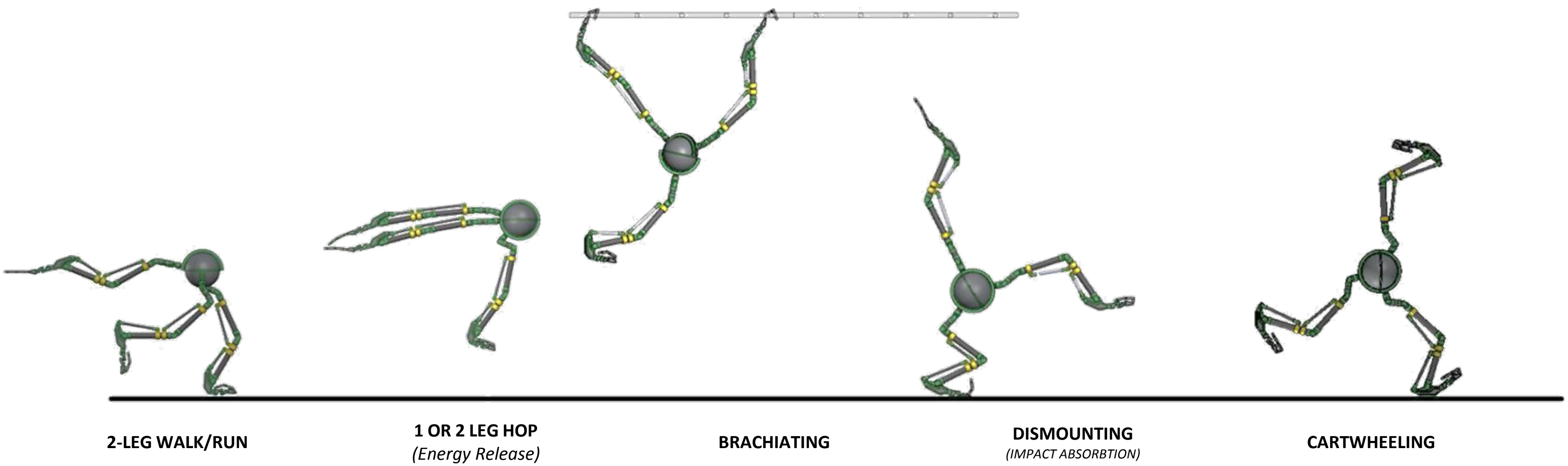


Gaits & Transitions

Variety of gaits can be realized using 3-limb configuration

By combining locomotion and manipulation into a single limb, a three legged body concept can be used for a variety of gaits. In the images below, the limbs can be arranged to form:

- **Two-Legged walk/run:** Two limbs are used as legs, with the third limb being used as a tail to add stability and/or manipulation
- **One or Two Legged Hop**: One or two limbs are used to store and release energy to hop while the third limb is used for either stability or manipulation tasks
- **Brachiating:** Limbs are used to grab objects overhead. Legs that are not in contact can swing with the body to reach the next object.
- **Dismounting:** Compliance members in the limbs absorb impact energy as the robot comes in contact with the ground
- **Cartwheeling**: Limbs contact the ground in succession. The limb in contact moves the body forward much like a leg in a walk or run mode. The body rotates in between steps to align the next limb for contact in the ground
- **Climbing:** All limbs can be used as manipulators to grab onto surface features. Two limbs maintain grasp while third limb moves to next position (not shown)

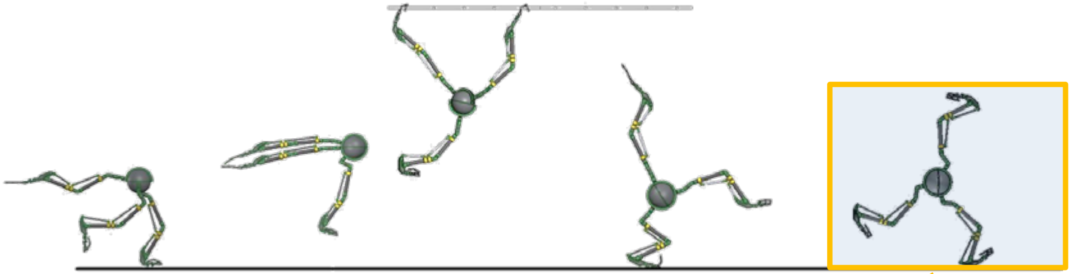


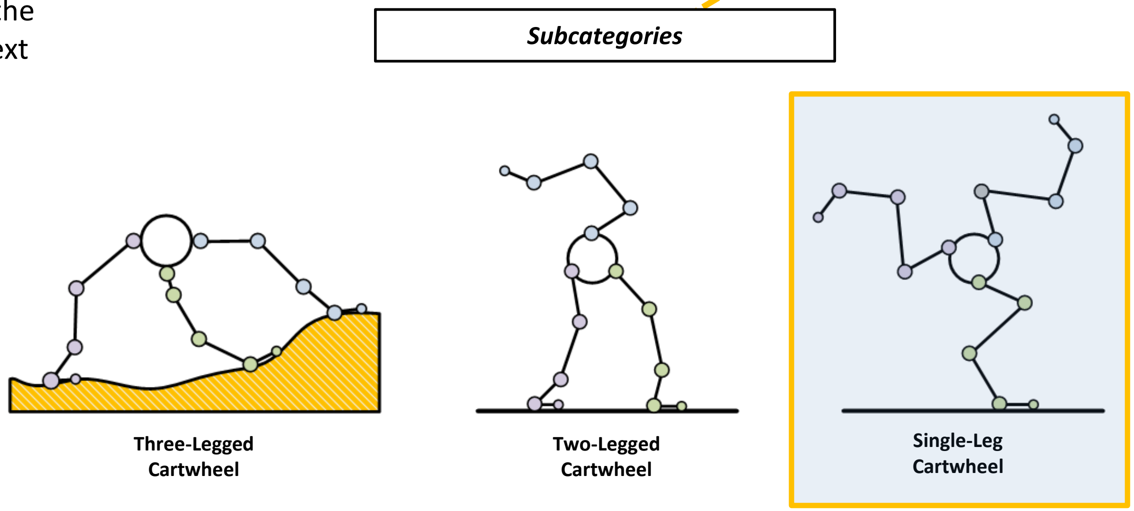
Gaits & Transitions

Variety of gaits can be realized using 3-limb configuration

Three example sub-categories of Cartwheeling are:

- **Three-Legged:** Each step results in all three limbs being in contact with the ground. Used when high stability or climbing required.
- **Two-Legged :** Two limbs remain in contact after each step. The body and third limb swing in between steps to position it for contact.
- **Single-Leg:** One limb remains in contact during each step. In between steps, limbs leave the ground and the body rotates during its free-fall phase to align the next leg for contact.





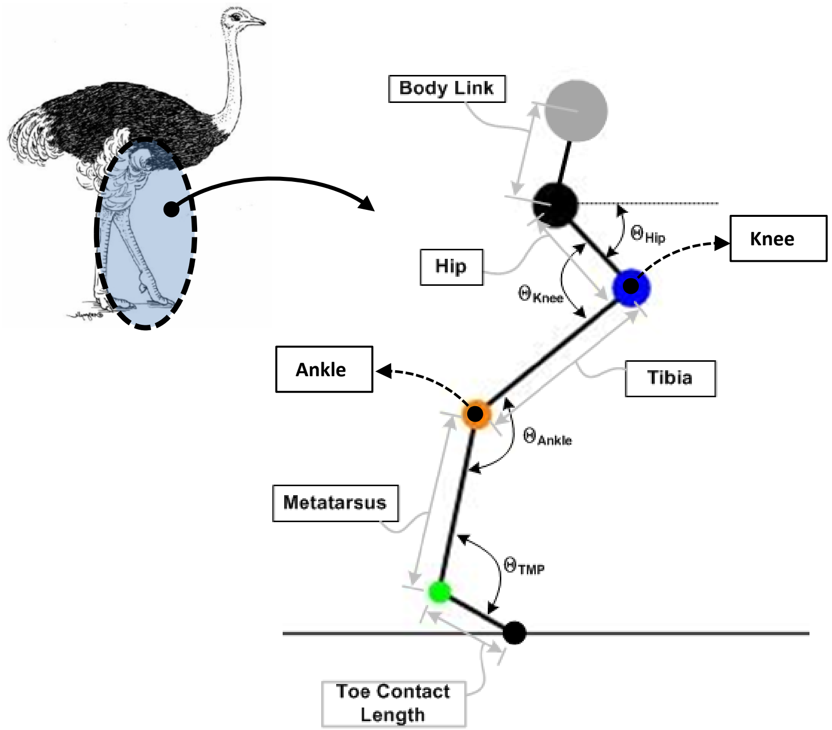
For the analysis shown in this work, the <u>One-Legged cartwheeling mode will be investigated</u>.

Limb Model

Inspired by biological model

Mechanical data from the single-leg cartwheel gait is required to select appropriate actuators. Therefore, a simple limb model is created using a biological model as a basis.

A 60kg ostrich is used as a biological inspiration for the joint structure of each individual limb due to its proven high speed mobility capabilities.



The limb model is used to create a dynamic gait model of the single-limb cartwheel which provides the following data as a function of time:

- *Joint Rotations*
- *Joint Angular Velocities*
- *Joint Actuation Torque*

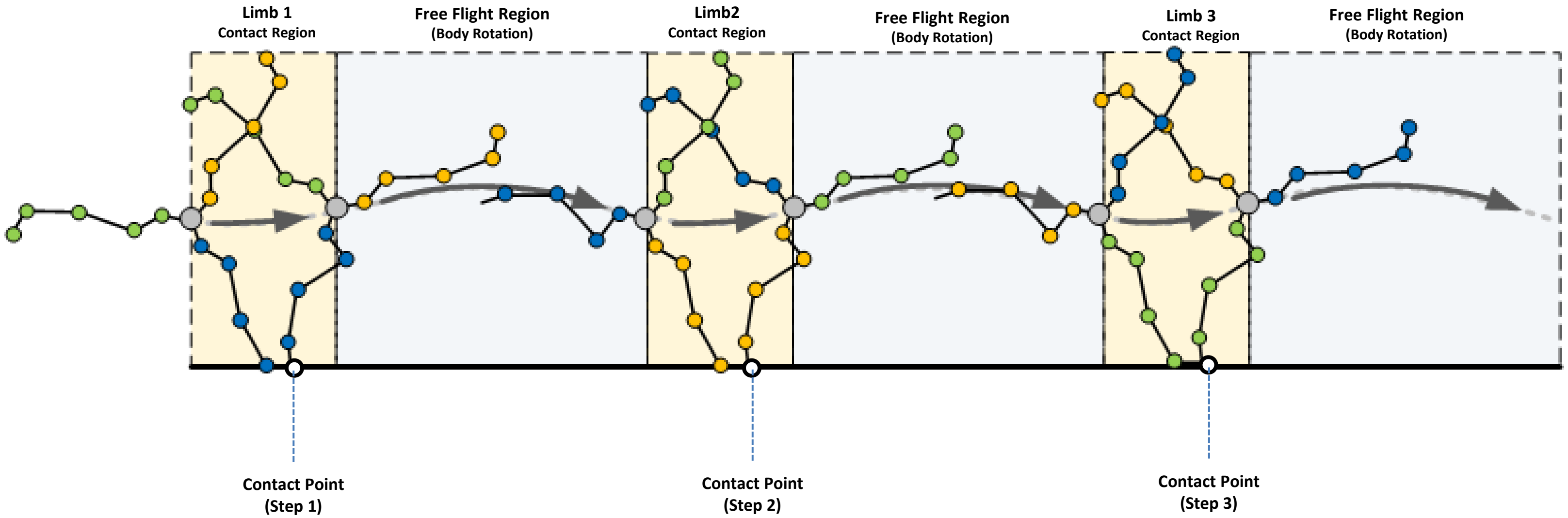
Single-Leg Cartwheel Gait

Body rotation during gait aligns limbs for contact

The single-leg cartwheel gait is similar to how many animals run but differs in the addition of a body rotation during the free-flight region to allow for the next limb to be aligned for contact.

The Gait has the following steps:

- Limb 1 contacts with the ground.
- Body swings forward as elastic energy is stored into mechanical elastic linkages
- Limb releases potential energy to launch into air
- While mid-air, Limb 2 swings to induce a forward body roll, aligning it for contact with the ground
- Limb 2 contacts the ground
- Body swings forward as elastic energy is stored into mechanical elastic linkages
- Limb releases potential energy to launch into air
- While mid-air, Limb 3 swings, inducing a forward body roll, aligning it for contact with the ground
- Limb 3 contacts the ground

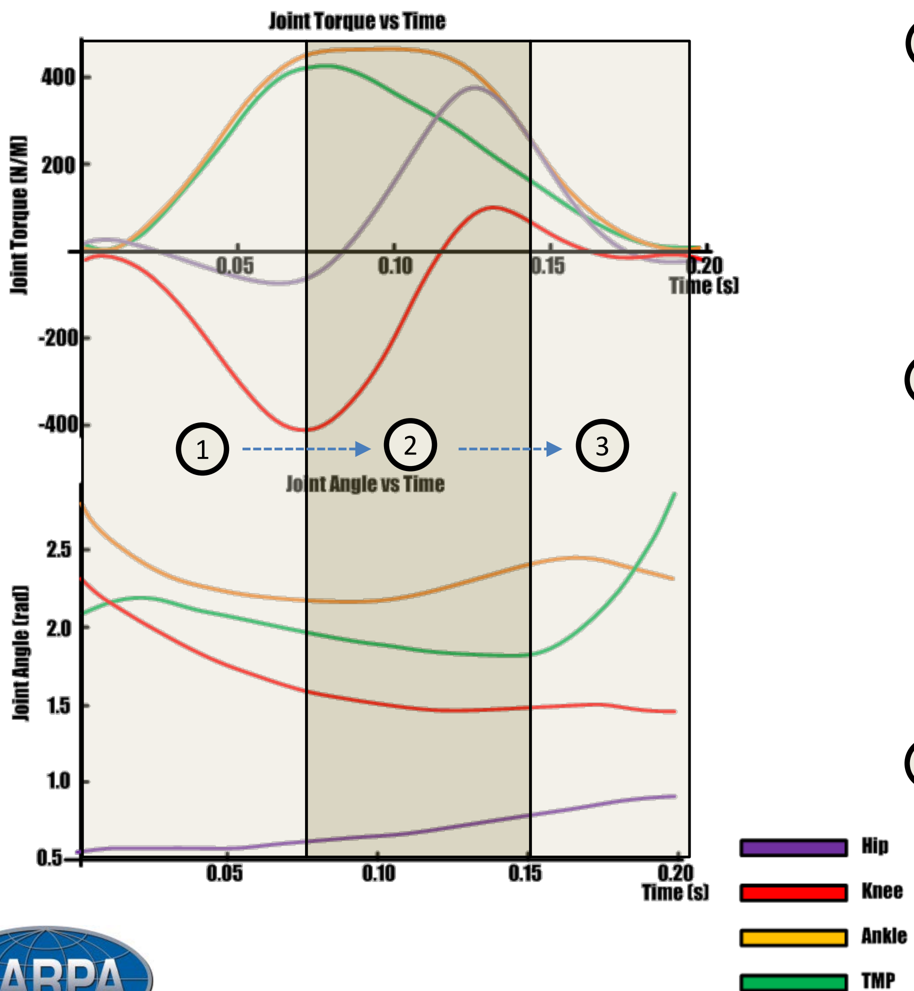


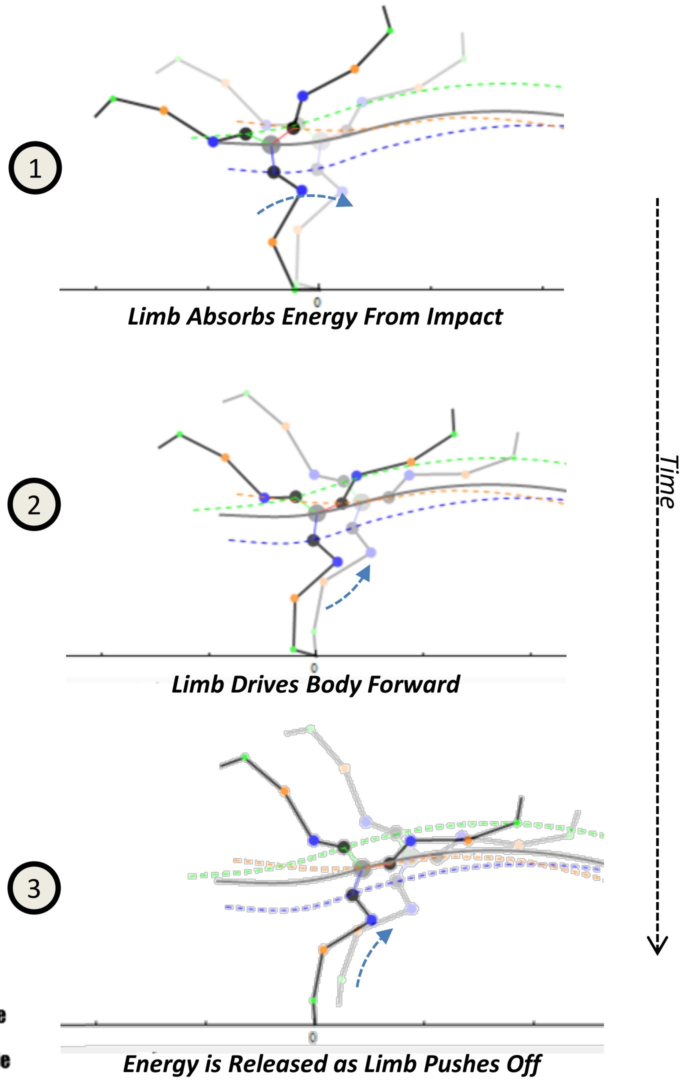
A video showing the single-limbed cartwheel gait is included with the presentation pack.

Dynamic Model

Simulation Results

The resulting limb torques, angles, and velocities were derived for a single contact region (t=0.2 s) from the dynamic simulation.

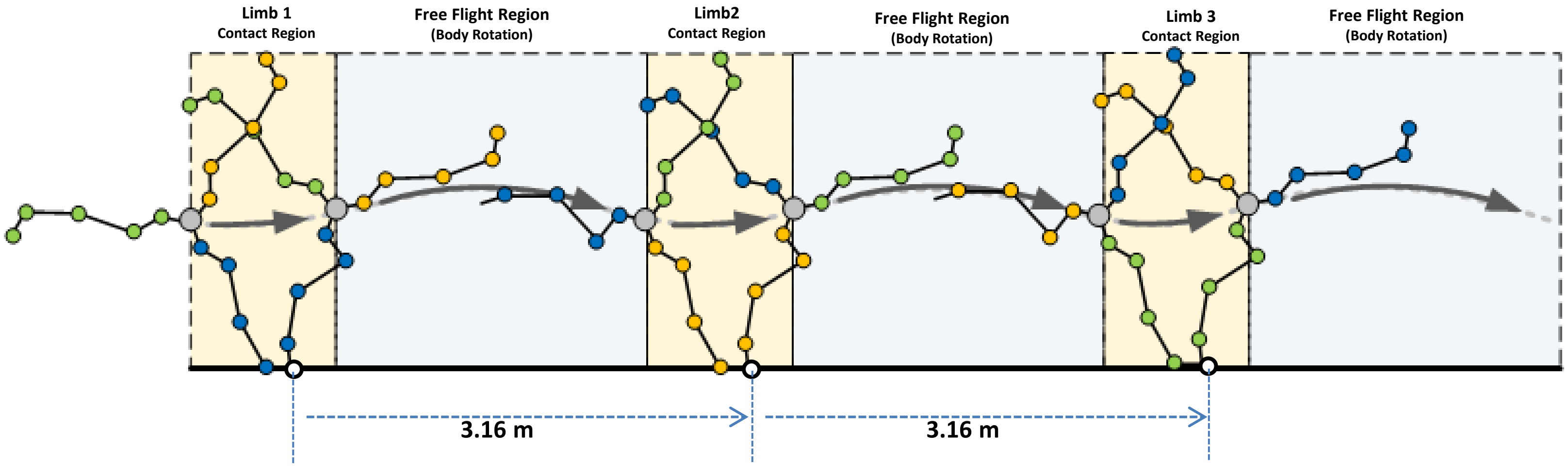




Dynamic Model

Simulation Results

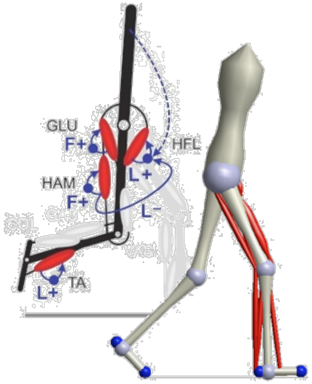
The jumping motion from the release of elastic energy at the end of each step along with the body roll allows for the robot to cover more distance per stride.



The single-limb cartwheel takes one step every 0.62 seconds, making its effective speed 5.1 m/s (11.4 mph)

Neuromuscular Control

Improve accuracy and efficiency of model



The single-limb cartwheel gait can be further improved through the implementation of <u>neuromuscular control methods</u>.

Utilizes a Segmented Controller

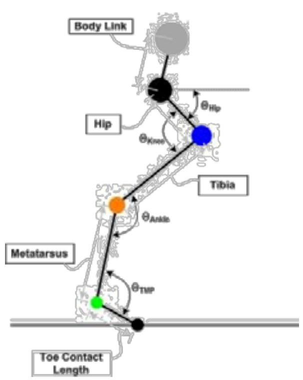
-Each link has its own local controller (module)

-Local controller encodes the physics of the link into the model

-Force feedback is coupled locally to dynamics and environment

-When two more modules are connected their coupled dynamics are considered as well as their local dynamics

-<u>Biarticulated actuation can be implemented using this approach</u>

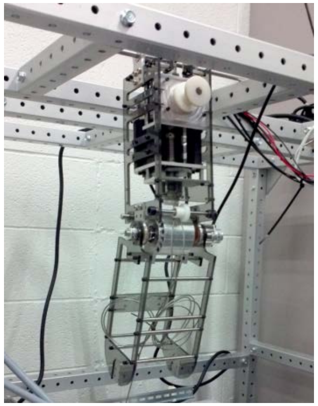


Works with deformable segments to cushion impacts

Inherently adaptable to unexpected changes in environment

-Automatic compliance from muscles

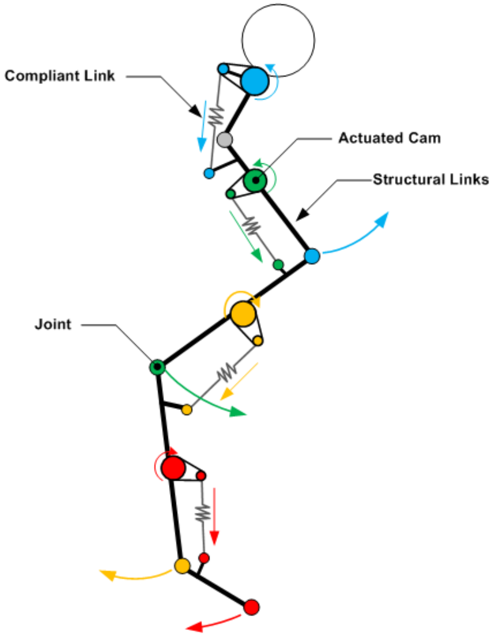
-Dynamic data for links are encoded into actuators (not all dynamic information of link is needed)



Simple Test Platform to Validate Neuromuscular Control

Limb Actuation

Several mechanisms are used to provide motion



Each limb is comprised of several mechanisms that provide actuation and compliance

<u>Structural Links</u>

Lightweight rigid structures that constrain motion between joints of the limb

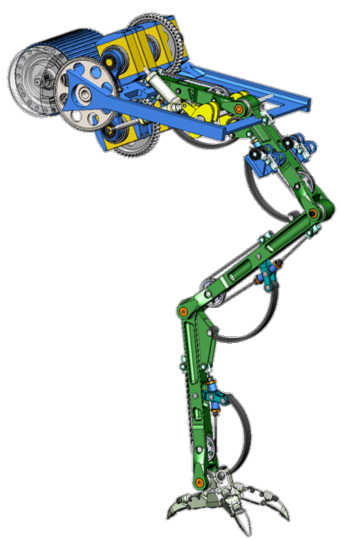
<u>Compliant Links</u>

Connecting members between structural links that have integrated compliance to absorb and release mechanical energy

- Provides impact absorption during running gaits
- Can be linearly actuated to provide high torque, accurate limb positioning *(mechanism covered after cam energy analysis).*

<u>Actuated Cam</u>

Rotary members that transfer rotational input (from motors & gearboxes) into reciprocal linear motion.



Prototype limb has been designed to integrate all of these components

Actuated cams located in upper portion of limb to reduce inertial load on moving links

- *Cams drive pulley system which translates rotation to links*
- *Variable Compliance links between cam and pulleys*
- *Non-Variable compliant link members between structural links can add more energy absorption as required.*

Mechanical Design

Reducing Inertial Loads

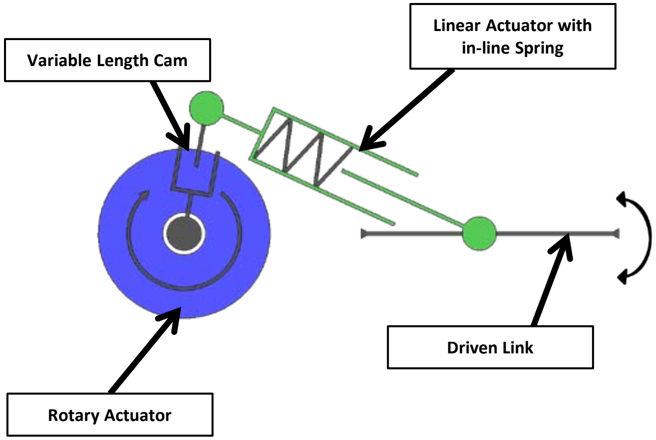
By minimizing the energy losses due to inertial changes of components, continuous motions can be efficiently produced through the implementation of rotary components.

An efficient actuator synthesis can be achieved by combining *Cams,* and *Linear Actuators* into a single, robust system

Cam / Linear Actuator Combination

- Cams efficiently converts continuous motion into oscillating motions, but when driven at a constant velocity are limited to a single output profile
- Varying the cam's speed throughout its rotation can produce multiple output profiles at the cost of inertial losses.
- Adding linear actuators into the links that connect to the cams allow for the oscillating path to be adjusted ***on-the-fly***
- Allows for gait specific paths to be generated
- Adding a spring in line with the linear actuator allows for joint compliance and energy storage.

Combination of Linear Actuators with Actuated Cam



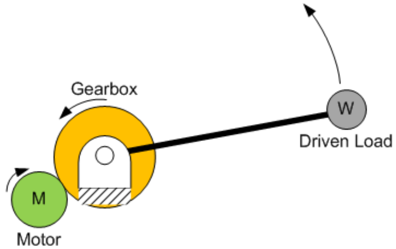
Actuation Analysis

Multiple Mechanical Methods compared for Maximum Efficiency

Multiple actuation methods for driving rotary motion are investigated to compare their inertial losses which the goal of finding the *most efficient* configuration.

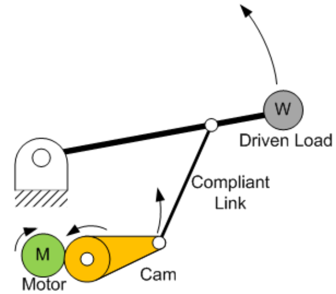
Option 1: Direct Drive

The limb is actuated directly at the joint by a motor connected by means of a gear box.



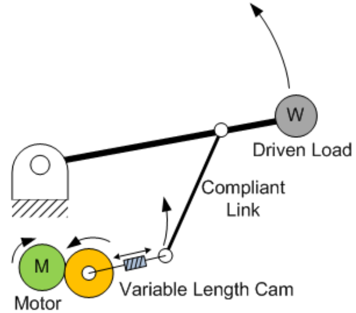
Option 2: Cam Drive

Motor drives the rotation of a cam which indirectly actuates the driven limb through a compliant connecting link.



Option 3: Variable Length Cam Drive

Motor drives the rotation of a cam which indirectly actuates the driven limb through a compliant connecting link. A linear actuator in the cam can adjust the cam's length at any point during its rotation.



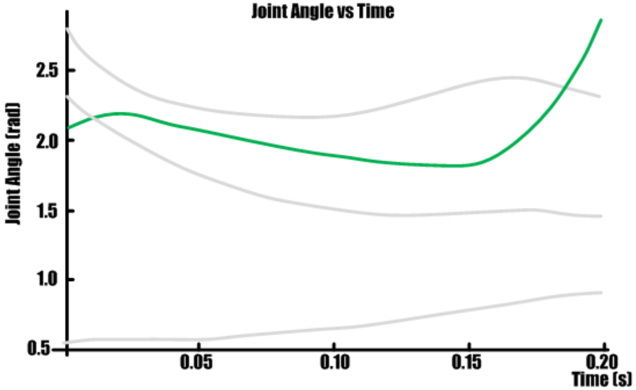
Actuation Analysis

Multiple Mechanical Methods compared for Maximum Efficiency

Using the <u>TMP joint</u> (between the metatarsus and toe) is used an as example case, energy losses during the single-limb cartwheeling gait can be estimated to find the most efficient actuator option.

It can be assumed that each system will be doing an equal amount of work to move the link into the positions required during the gait.

Inertial losses, though, will vary between the three actuation methods due to how the input energy is applied to the output link.



The rotation of the joint can be used to estimate the inertial losses in the system from changes in angular speed.

$$\Delta KE = \left| \frac{I\omega_{t_2}{}^2}{2} - \frac{I\omega_{t_1}{}^2}{2} \right|$$

Losses between two time steps due to changes in inertial energy is equivalent to the absolute difference between the inertial kinetic energy at each time step.

Actuation Analysis

Inertial properties of drivetrain components

Inertial data from both the motor and gearboxes was estimated based on commercially available off the shelf components.

The motor's inertial properties were selected for a motor that could provide **4.9N-m** of Torque at a rated speed of **6000 rpm**.

A conservative estimate of the rotor's moment of inertia is used for the analysis is **2.1 E-04 kg-m^2**

For the direct drive case, a 100:1 gearbox would be required to produce the output torque required for the gait.
Data was compiled from a collection of commercially available off the shelf gearboxes that are sized for the input motor load above.

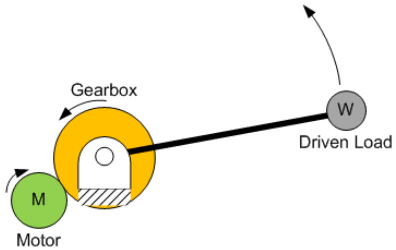
A conservative estimate of an appropriately sized 100:1 gearbox's moment of inertia is **1.76 kg-m^2.**

For the analytical cases where a cam drive is used, a smaller 25:1 gearbox is needed to produce the output torque required for the gait due to an inherent gear ratio in the cam system itself.

A conservative estimate of an appropriately sized 25:1 gearbox's moment of inertia is **0.096 E-02 kg-m^2 .**

Actuation Analysis

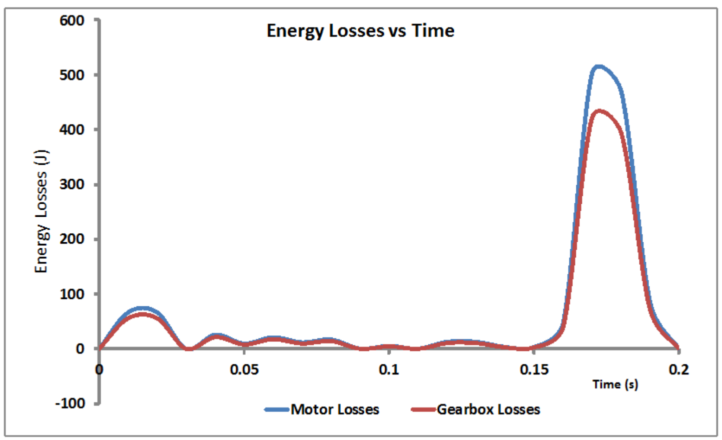
Direct Drive Inertial Losses



The direct drive method is able to match an exact output profile for the limb. Doing this causes very high velocity changes in the motor.

The motor runs at a rate of 100x the required speed of the output (through the gearbox) causing the inertial losses from the motor to be magnified *(at a rate of the gear ratio^2).*

In this method, it is assumed there is no compliance in the link member so that the input profile can exactly match the output profile



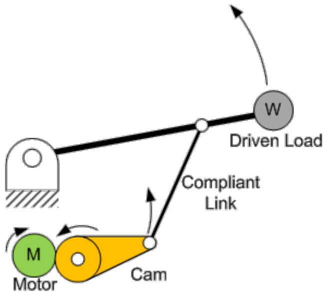
Energy Loss from Motor: **1.36 KJ / Step**
Energy Loss from Gearbox: **1.14 KJ/ Step**

Distance Traveled each Step: 3.16 m

Rate of Energy Loss: 0.79 KJ/m

Actuation Analysis

Compliant Link

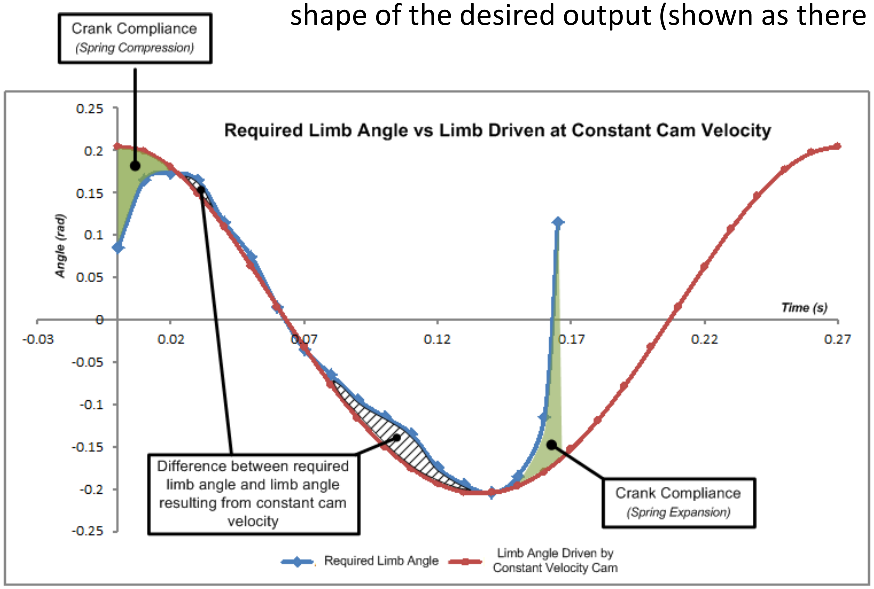


The compliant link that connects the cam to the driven link has inherent compliance that can store energy on impact and release it at the end of the stride.

The crank compliance reduces the amount of angular rotation required from actuator.

- *Compliant link compresses during initial impact*
- *Energy is released from compliant link as limb drives body into free flight phase.*

By driving the cam input at a constant velocity, an output profile can be produced that matches the overall shape of the desired output (shown as there red line in the plot below).



The differences between the two output profiles is made up by changing the instantaneous speed of the cam throughout the gait profile.

If the output link requires extra rotation, the cam would increase its velocity to move the output the extra amount.

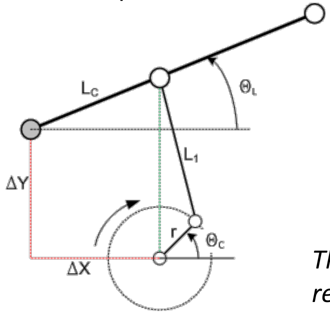
Even though this helps match the required gait profile, there are inertial losses due to the cam's change in velocity.

Actuation Analysis

Cam Drive

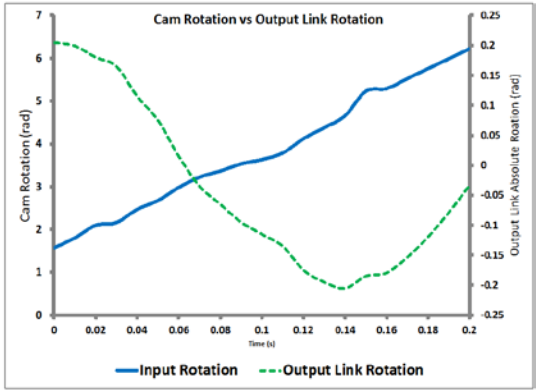
The velocity of the cam is adjusted throughout its rotation to match the required output profile.

The cam drive geometry below was used as an example case to develop the input/output relationship between the cam and the output link



ΔX = 100 mm
ΔY = 100mm
Cam Radius (r) = 20.375 mm
Compliant Link Length (L_1) = 100 mm
Distance Between Output Link Pivot
and Compliant Link Connection (L_C) = 100mm

The geometry shown allows for the output link to move in all the required positions to perform the required gait path (+- 11.73 degrees)



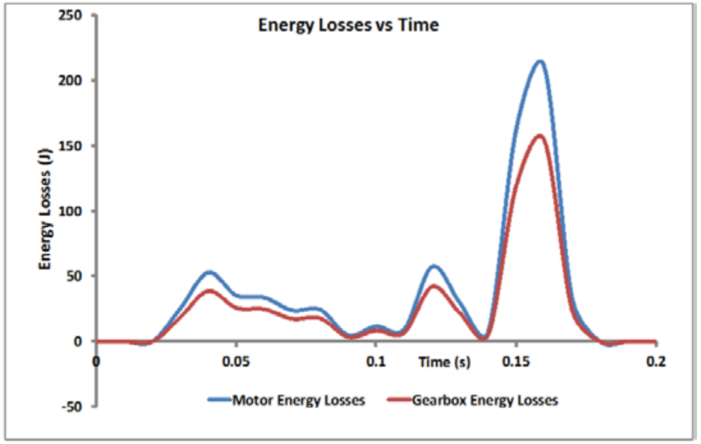
As shown in the plot above (right), the cam is driven at <u>varying speeds</u> to move the output link into the appropriate position to match the gait profile.

The total energy loss for a single step can be determined using the inertial data estimated for a 25:1 ratio motor/gearbox drivetrain for the cam.

Energy Loss from Motor: **0.72 KJ / Step**
Energy Loss from Gearbox: **0.52 KJ/ Step**

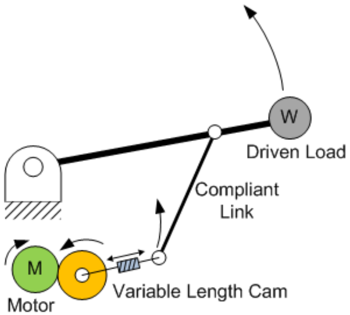
Distance Traveled each Step: **3.16 m**

Rate of Energy Loss: 0.39 KJ/m
(Savings of 0.4 KJ/m compared to Direct Drive Method)



Actuation Analysis

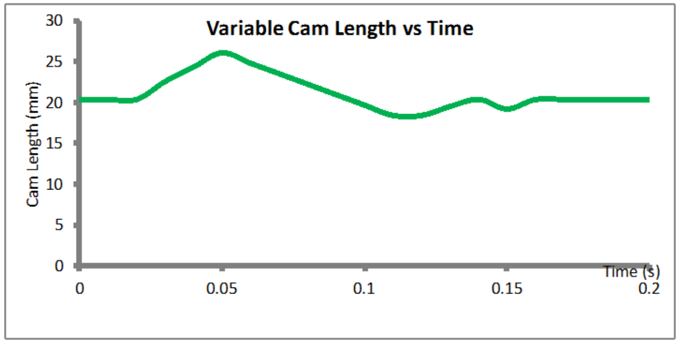
Variable Cam Drive

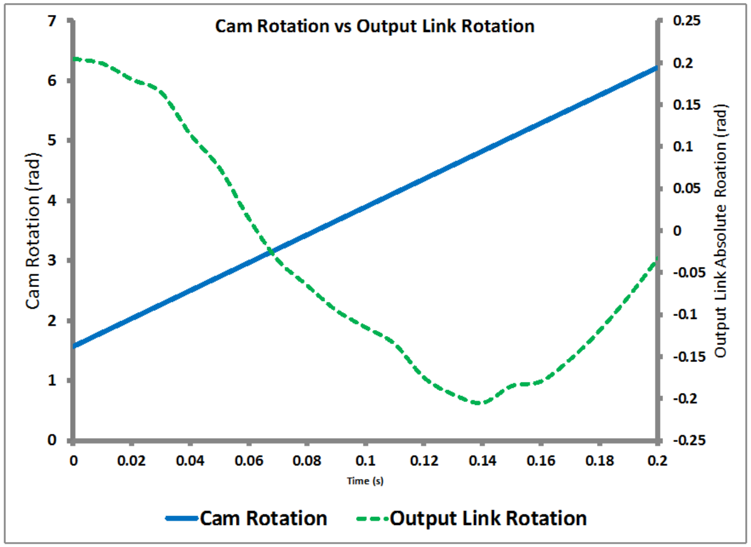


The cam length can be adjusted throughout the cam's rotation using the Variable Cam Drive concept to match the output link's rotation to a desired profile.

The plot to the right shows the length adjustment of the cam throughout its rotation.

Longer cam lengths cause the output link to rotate a greater amount for the same cam input rotation





Using this method, the cam can be driven at a constant velocity, **reducing inertial losses in the cam's drivetrain to zero** throughout the stride.

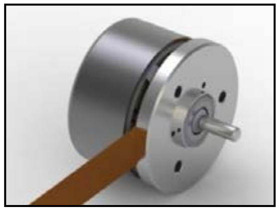
The inertial losses in the system are not limited to the motion of the drive components for the variable length cam.

Actuation Analysis

Variable Cam Drive – Linear Actuation Energy Losses

The linear adjustment in the cam mechanism is realized through the use of a smaller motor, gearbox, and lead screw drive system *(compared to the larger motor that drives the cam's rotation)*

DC Motor

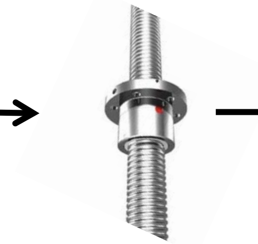


Rotor Inertia: 35 g-cm^2

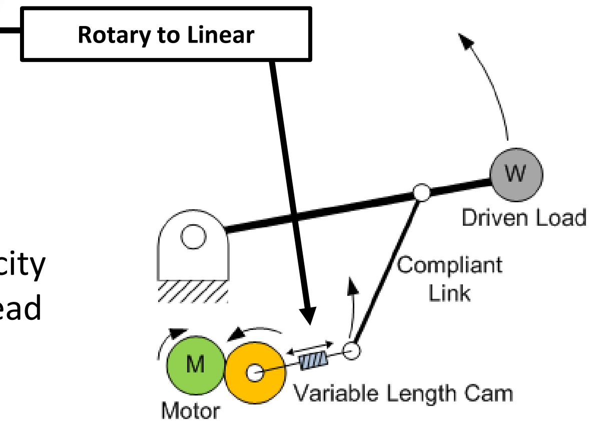
111:1 Gearbox

Mass Inertia: 89 g-cm^2

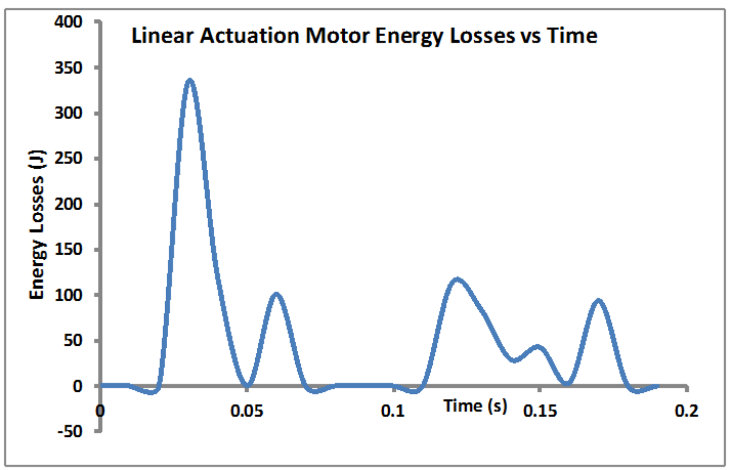
Lead Screw



10 mm / turn



The majority of inertial losses from the variable length cam are due to velocity change in the DC motor (which is running at a 111 times the speed of the lead screw)



Energy Loss from Motor:	**0.84 KJ / Step**
Energy Loss from Gearbox:	**Negligible**

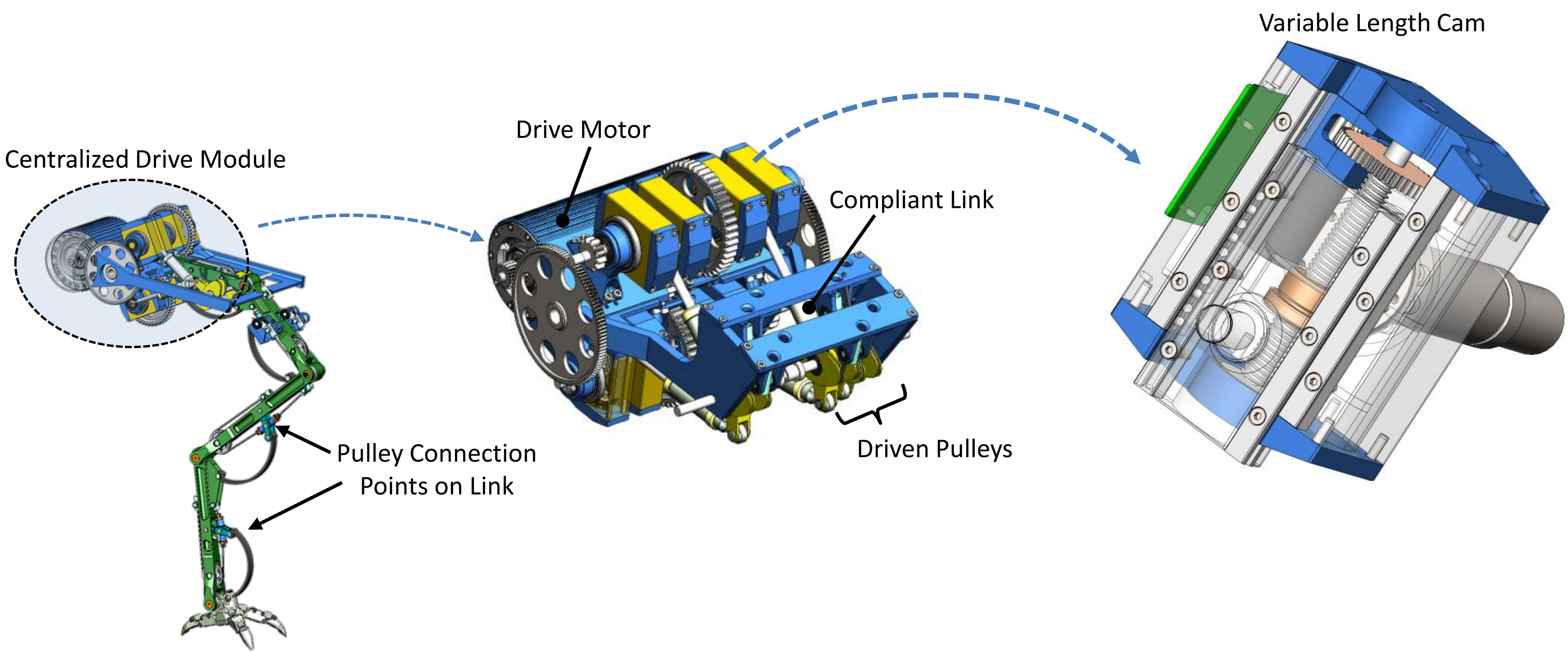
Distance Traveled each Step: 3.16 m

Rate of Energy Loss: 0.266 KJ/m
(Savings of 0.124 KJ/m compared to Standard Cam Drive)

Mechanical Design
Limb Actuation System

A full limb mechanical design concept was developed that integrates the variable length cam drive into a centralized drive module at the hip end of the limb.

To reduce the weight and inertial loading on the structural driven links in the limb, the variable length cams drive pulleys which, in turn, actuate the limb's links.



Mechanism Design

Variable Cam Drive

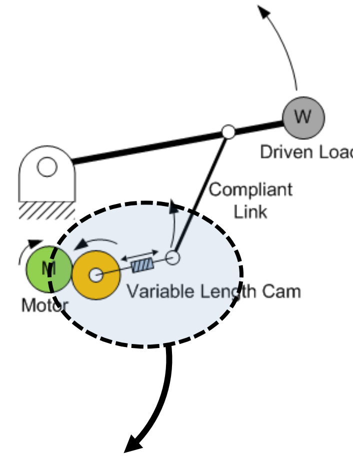
Based on the validity of the variable cam drive mechanism in the actuation analysis, a prototype system was developed.

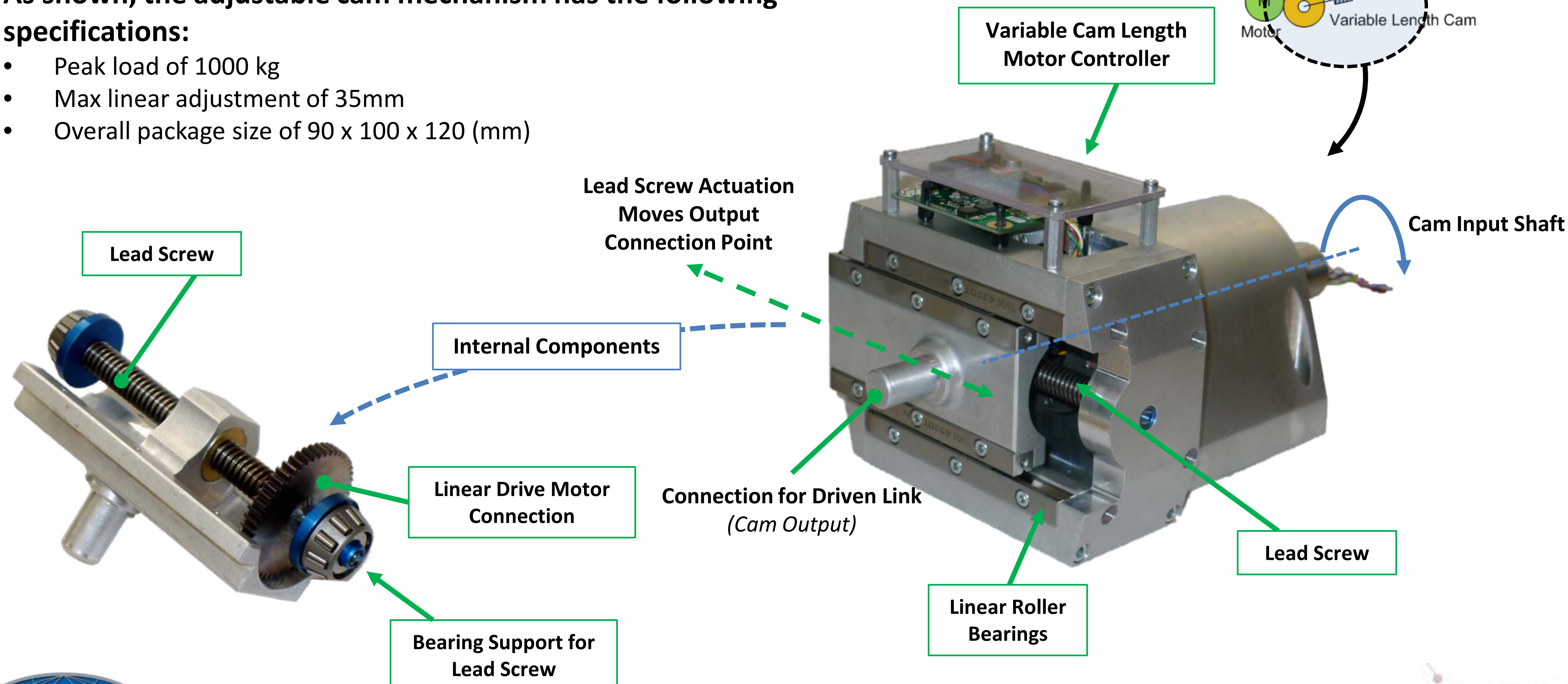
The prototype shown mirrors the concepts shown in the actuator analysis.

Several components in the system were scaled in comparison to the analysis to reduce cost and time to manufacture through the used of commercially available off-the-shelf components rather than custom designs.

As shown, the adjustable cam mechanism has the following specifications:

- Peak load of 1000 kg
- Max linear adjustment of 35mm
- Overall package size of 90 x 100 x 120 (mm)



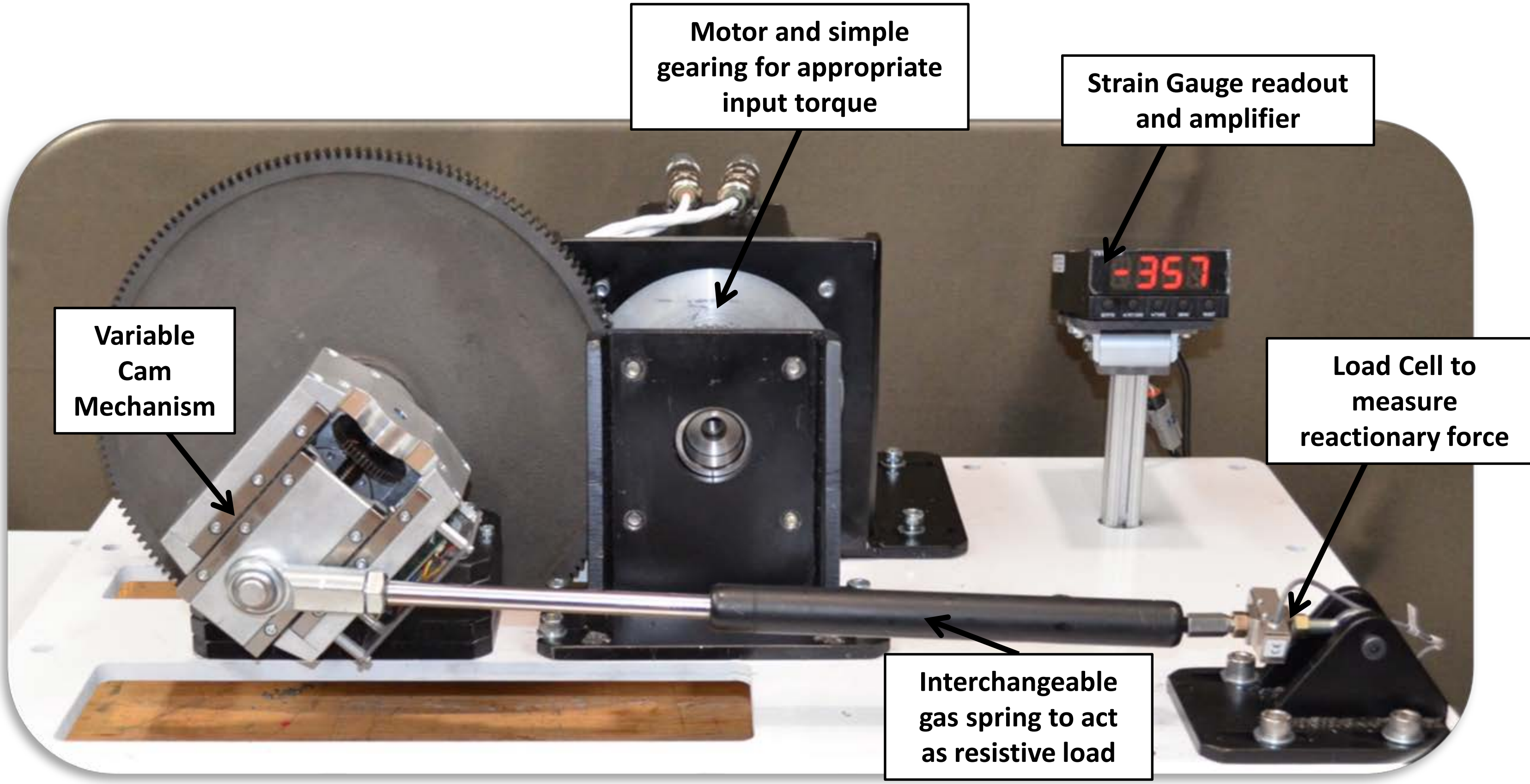


Variable Cam Prototype Testing

Limb Actuation System

A test stand was created to validate the feasibility of the variable length cam.

In this setup, the variable length cam drives against a gas spring to simulate actual loading conditions.

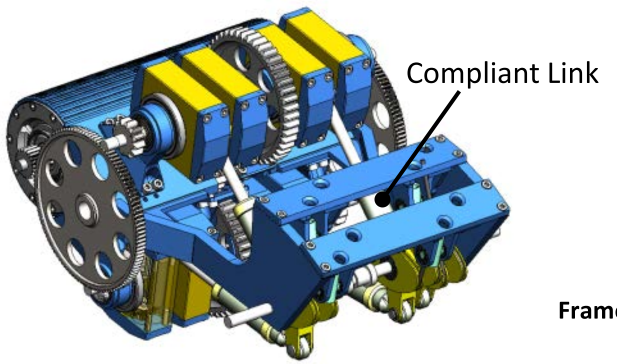


A video showing the variable length cam with varying cam lengths is included with the presentation material.

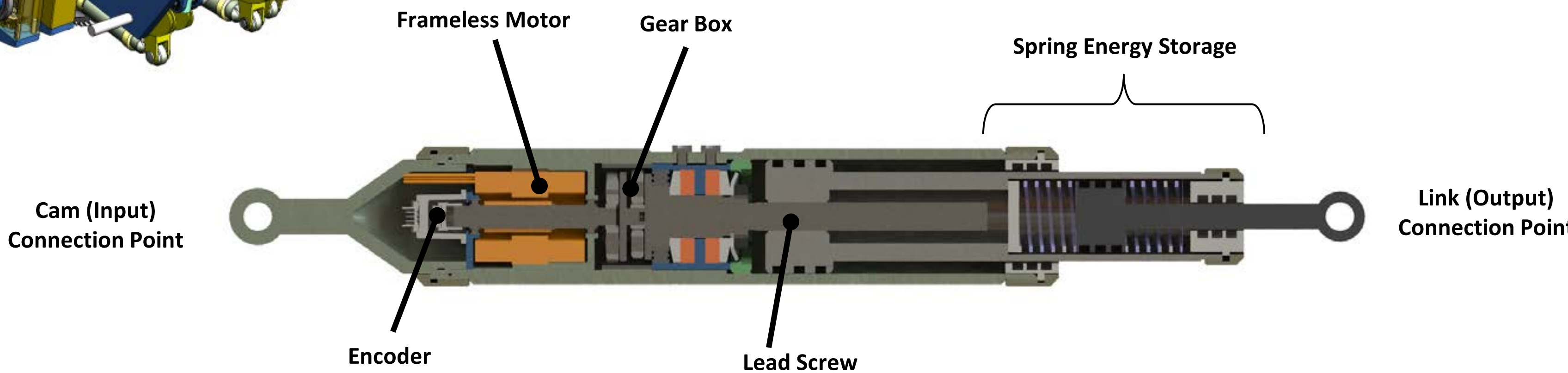
Mechanical Design

Linear Compliant Links

Another integral part of the limb actuation system is a variable compliance link member. In this phase of the study, only the concept and mechanical design has been realized.



During <u>mobility</u> tasks, the compliant link is able to storage kinetic energy in the spring. The lead screw can be used to ‘tune’ the spring to a desired level to maximum efficiency.



During <u>manipulation</u> tasks, the lead screw drive in the compliant link can be used as a linear actuator for fine positioning.

Initial estimates show that a system can be designed that can output 300 lbs of force for a package weighting 0.3 kg or up to 1000 lbs of force for a 1kg module.

Gear Design and Testing

Weight and Inertia Reduction

The actuator analysis showed the importance of reducing inertial loads to increase the efficiency of legged mobility. Another way to reduce those inertial loads is to lighten the heavy gear train components in the drive system.

A test set-up was developed that can determine the loading characteristics of a wide array of gears in both peak loading conditions and cyclic loading conditions.

Peak Loading Conditions: Tests for ultimate strength of gears

Cyclic Loading Conditions: Tests how the gears perform under loading conditions that might be realized from a running limbed robot gait.

The cyclic loading data needs to be created since it is not a standard testing value performed by gear manufacturers.

The results from the test can lead the mechanical design of gearboxes and drive systems for any legged mobility platform.

Gears can be sized appropriately using the cyclic loading data so that inertial loads are reduced, increasing the overall efficiency of any limbed robot.

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Gear Design and Testing

Limb Actuation System

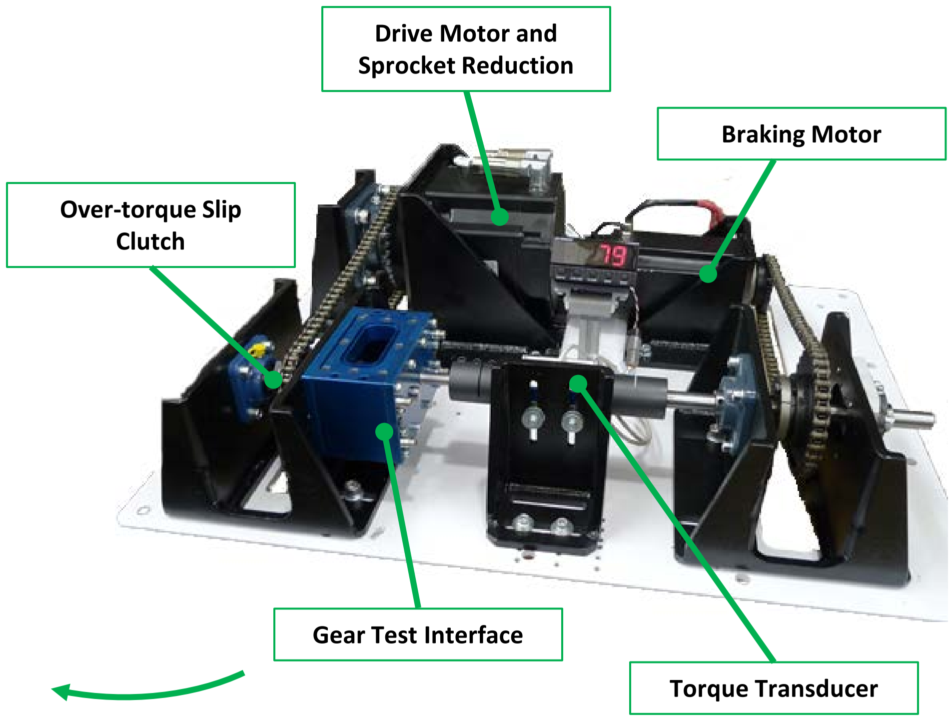
The test rig has been constructed, but test data will not be available at the time of this report.

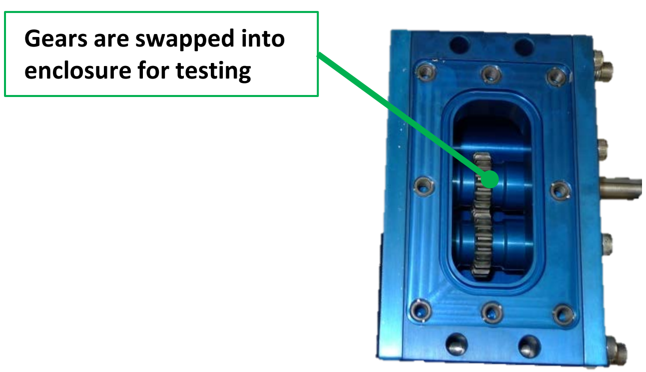
For meaningful test results, each gear will need to undergo tens of hours of testing under load per trial.

During testing, the gears will be driven by the drive motor while having a resistive load from the braking motor.

The gears will be run in over time to determine their capability to handle increasing brake loads.

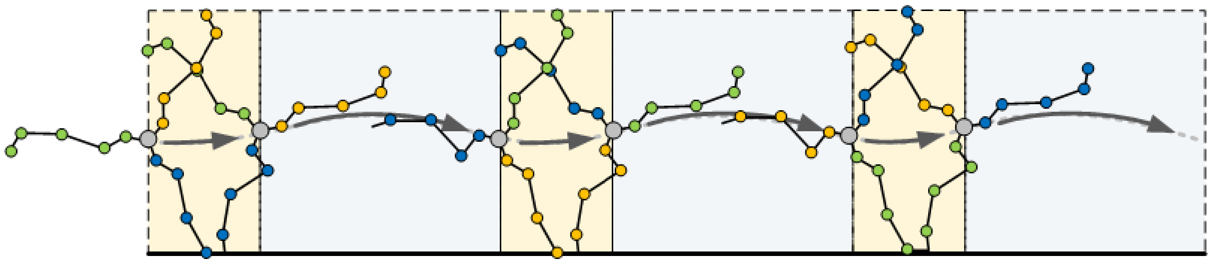
An ultimate load for each gear type will be determined based on braking load.



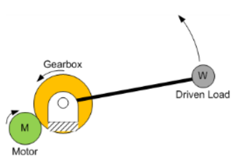
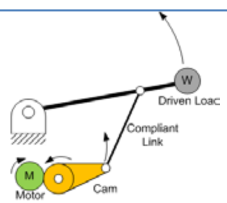
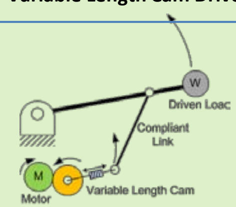


Conclusions

In this report, a novel <u>triple-limbed robot with compliant joint structure</u> was shown to be capable of a series of novel locomotion gaits. The <u>single-limb cartwheeling gait</u> was analyzed to determine its feasibility.

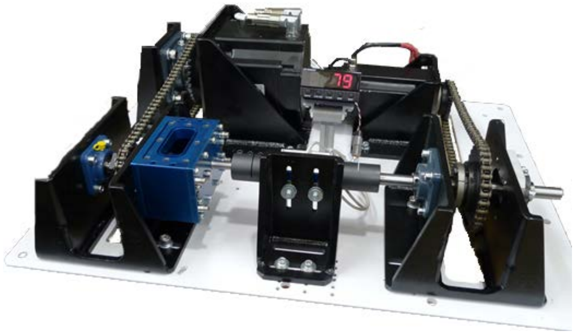


Using data produced from a simulation of the single-limb cartwheeling gait, various actuation methods were compared to measure the inertial losses incurred to match a desired limb output profile.

	Actuation Type	Direct Drive	Standard Cam Drive	Variable Length Cam Drive
	Mechanism Layout			
Inertial Losses	Cam Drive Motor	0.43 KJ / m	0.23 KJ / m	0 KJ / m
	Cam Drive Gearbox	0.36 KJ / m	0.16 KJ / m	0 KJ / m
	Linear Drive Motor	N/A	N/A	0.266 KJ / m
	Linear Drive Gearbox	N/A	N/A	Negligible
	TOTAL	**0.79 KJ / m**	**0.39 KJ/ m**	**0.266 KJ/m**

65 % Reduction Compared to Direct Drive
31% Reduction Compared to Standard Cam Drive

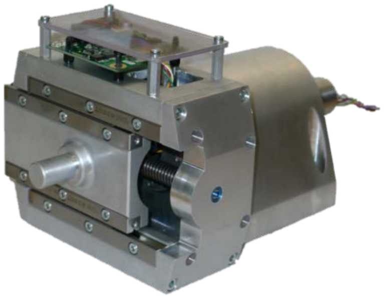
Conclusions

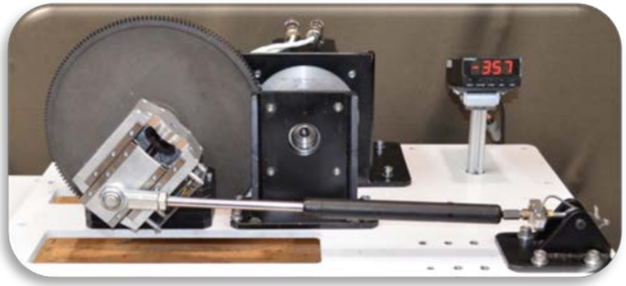


Further inertial energy losses can be mitigated by reducing gear and drivetrain weights. A gear testing device was developed which will provide loading data for gears made of various materials under normal and cyclic loads.

The results from this test can lead the design of efficient gear trains with minimal moments of inertia.

The variable length cam concept was realized in a prototype version showing how it could be realized with commercially available off the shelf components. The mechanism can be further improved through the use of custom designed components, which would decrease overall system weight and increase performance.





A test set-up was developed to demonstrate the potential for the variable length cam to provide enough output force for the novel single-limb cartwheeling gait.

A linearly actuated compliant link member concept was shown which could either:

- provide energy storage/release during **mobility** tasks

- Or provide linear actuation for **dexterous manipulation** tasks.